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Coastal geoheritage: encompassing physical, chemical, and biological processes, landforms, and other geological features in the coastal zone

M Brocx[1] & V Semeniuk[2]

[1] Division of Science & Engineering
Murdoch University, South St., Murdoch, WA, 6150
[2] V & C Semeniuk Research Group
21 Glenmere Rd., Warwick, WA, 6024

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Abstract

The coast is one of the most complex environments on the Earth's surface, being a zone of intersection and interaction of land, sea, groundwater, and atmosphere and the processes therein, and carries processes and products that are either not present or only weakly developed elsewhere. With other matters such as lithology, structure, or geological framework being equal, the coastal zone is one that generally results in greater geodiversity than elsewhere. The range of interacting physical, chemical and biological processes in the coastal zone include: waves, tides, storms, and cyclonic activity (all resulting in erosion, sediment mobility, particle size sorting, sedimentary structures); development of a splash zone; onshore winds resulting in shore-directed wind waves and longshore drift, and in erosion, transport, particle sorting, lag deposits, and dune building; sedimentation mediated physically by fluvial influx, longshore and/or onshore transport, and tidal currents, or biologically by skeletal production; bioerosion; chemical erosion; salt weathering; tidal invasion of coastal sedimentary bodies by seawater; evaporation and transpiration; hydrochemical effects such as solution, or precipitation of carbonates, gypsum, or halite; fresh-water seepage and its effect on ecology and coastal erosion; sediment delivery fluvially; and biological effects including skeletal production, encrustation, biostrome and bioherm building, grain fragmentation, and bioturbation. A significant factor also is the prevailing nature of many of the processes therein. Coasts commonly exhibit shore-normal environmental gradients and hence a graded expression of processes, resulting in variation in complexity and geodiversity in physical, geochemical and biological products across the shore, and variation in fine- to small-scale stratigraphic sequences. To provide a perspective of the expression of any geodiversity of bedrock, and of the diversity and complexity of sedimentary systems in the coastal zone, selected coastal zones are compared with terrestrial environments for specific rock types, and specific sedimentary sequences – while there is overlap, coastal environments present greater complexity and geodiversity of physical, chemical and biological products. Because they interface with oceans, coastal deposits and coastal forms also can record a history of sea level, climate, and oceanic processes. It is the range of sedimentological and erosional features, expressed geomorphologically and stratigraphically along the coast, and their strength of development, that sets coastal geoheritage apart from continental (or inland) geoheritage.

Keywords: coastal geoheritage, coasts, geoheritage, geoconservation, geodiversity

Introduction

Geoheritage, a term evolved from and synonymous with "geological heritage" (Anon 1991a; Joyce 1994; O'Halloran *et al.* 1994; Brocx & Semeniuk 2007), and now used internationally, as well as in Australia, carries the notion of the heritage of features of a geological nature. The terms were recently afforded formal status, beyond their use in geoconservation and environmental management, by the launching of a new Journal, *Geoheritage*, entirely devoted to the issues of geological heritage, geoconservation, theory and ideas underpinning geoheritage and geoconservation, and management of sites of geological significance, and by the International Union of the Conservation of Nature (IUCN 2008) as Resolution 4.040 Conservation of geodiversity and geological heritage (adopted as CGR4.MOT055), adding geoheritage to its conservation agenda.

In its scope, the general term *geoheritage* encompasses intrinsically important, or culturally important geological sites that are of global, national, state-wide, to local significance (Brocx & Semeniuk 2007) that include igneous, metamorphic, and sedimentary rocks, and stratigraphic, structural, geochemical, mineralogic, palaeontologic, geomorphic, pedologic, and hydrologic features, at all scales, that offer information or insights into the formation or evolution of the Earth, or into the history of science, or that can be used for research, teaching, or reference. Sharples (1995) expanded the original idea of geoheritage to include the protection of dynamic geological processes and geodiversity for their inherent or intrinsic values. Geodiversity is the term used to denote the diversity of geological features present at a given site or region (Brocx & Semeniuk 2007).

Features of geoheritage significance are to be found in many locations and environments around the globe, and can range from crystal-scale, fossil-scale, bedding-scale, cliff-scale, to systems scale (see Figure 2 in Brocx & Semeniuk 2007). Examples include: (as crystals) the Jack Hills Archaean zircons in Western Australia (Wilde *et al.* 2001; Cavosie *et al.* 2004), (as fossils) the Precambrian Ediacaran fauna in South Australia (Glaessner 1966), (as bedding-scale features) the eurypterid tracks on rippled sandstone in the Tumblagooda Sandstone in Western Australia, (at cliff scale) the unconformity at Siccar Point in Scotland, and (at systems scale) the Grand Canyon in the USA and the Shark Bay area in Western Australia (Holmes 1966; Shelton 1966; Logan & Cebulski 1970; Logan *et al.* 1970; Playford 1990). From a location perspective, sites of geoheritage significance occur in a variety of landscape settings, climatic settings, and geological provinces, from eroding landscapes in arid zones (Monument Valley, Arizona) to eroding landscapes in alpine regions (Mount Blanc, Switzerland). Each may carry with it relatively simple processes and products or an array of complicated and interacting processes and products. Thus, there is quite a variety of recognised sites of geoheritage significance in the world, some significant because of their crystals and fossils, some because of their large-scale attributes, such as structural/tectonic features, and some because of the collective ensemble of a suite of large-scale to fine-scale features involving geological, geomorphological, lithological, and pedological attributes, amongst others (*e.g.*, Shark Bay). In this context, geoheritage addresses the importance of geological sites in their complexity, diversity, and values scientifically, culturally, educationally, and for reference and research.

Of all the environments on the Earth's surface, one of the most complex is the shore zone. With other matters such as lithology, geological structure, or geological framework being equal, it is an environment that results in more complexity and geodiversity (*i.e.*, varied assemblage of geological features) than other environments represented elsewhere. As with other environments, the complexity and geodiversity developed along the coast are variable according to parent rock types, sediments, and other materials, biodiversity, hydrochemical effects, diagenesis, and variable according to environmental setting and climate.

In this paper we explore the various features of geology (and geomorphology as a subset of geology), expressed as geodiversity in the coastal zone as a prelude to identifying coastal types and sites that may have geoheritage significance (to be developed in later works). Under the umbrella term, *coastal geoheritage*, we explore the reasons for coastal geodiversity, *i.e.*, the physical, chemical, and biological processes, landforms, and other geological features that occur in the coastal zone, and formally recognise that coastal geodiversity and coastal geoheritage are especially significant in a context of geoconservation. To place the complexity of the coastal zone in perspective, and hence the geodiversity of the coastal zone into perspective, rocks and sediments in the coastal zone are compared with those in terrestrial environments, *e.g.*, a Pleistocene calcarenite exposed at a rocky shore with that exposed in an inland cliff, and an accreting upward-fining sequence of tidal flat sediment with that of a point bar, amongst other examples.

The term bedrock is used in this paper to refer to indurated rocks of sedimentary, igneous, and metamorphic origin, of Precambrian to Phanerozoic age (*e.g.*, the Silurian Tumblagooda Sandstone, and the Mesozoic Broome Sandstone), and not only to Precambrian basement rocks.

Definition of *coast* and *coastal*, and other terms

The term "coast" and its derivatives are reviewed and then defined here because the ideas of geoheritage and geoconservation will be applied to this very specific site of the Earth's environment.

Few texts define the term *coast*. Even encyclopaedia devoted to geomorphology (Fairbridge 1968), or to beaches and coastal environments (Schwartz 1982) do not address its definition, but rather focus on using its derivative as an adjectival descriptor, *e.g.*, *coastal* classification, *coastal* ecology, *coastal* erosion, and so on. A brief review of those texts dealing with coastal systems where the definition of *coast* is somewhat addressed (although not to any depth) is presented below.

Reineck & Singh (1980) use the term *coast* as the zone that separates continents from the sea. Davis (1978) defines a *coastal area* as the zone where land and sea meet, where there can be a variety of complex environments. Bates & Jackson (1987) define *coast* as the strip of land of indefinite width that extends from the low tide line inland to the first major change in landform feature. Woodroffe (2002) defines *coast* as the interface between land and sea.

In all definitions, generally, the term *coast* is applied to shoreline environments, usually for the strip of land that is located between high and low tide. Some authors extend the use of the term to environments in the nearshore breaker zone and extending to the nearshore supratidal zone. In Western Australia, for planning purposes, the *coast* is defined to include the coastal waters to a depth of 30 m, as well as reefs, estuaries, tidal rivers and land which is presently subjected to coastal processes (such as mobile dunes, areas inundated by storm surge, and vegetated foreshore areas exposed to onshore winds). In addition, the *coast* includes a fringe of stable land suitable for coast-related activities (Anon 1993).

The descriptor *coastal* is more general as a term, and has a broader scope in that it includes the *coast* itself and the adjoining area in the marine environment and terrestrial environment that are proximal to the coast, sometimes merely proximal geographically, but other times with an environmental inter-relationship implied (*e.g.*, deposits stranded inland by progradation, but having been formed by earlier coastal sedimentation; or within the reach of wave splash or salt spray). For instance, *coastal* is defined by Bates & Jackson (1987) as pertaining to a coast, bordering a coast, or located at or near a coast, and *coastal area* as the area of land and sea bordering a shoreline. However, there is general disagreement on how far inland and how far seaward constitutes *coastal* (Anon 1995a, 1995b).

While *coast* as a term may be more or less defined in the scientific literature, in the area of coastal planning policy for administrative purposes, *coastal* is less precise, with different definitions generated by coastal managers in the various Local Governments based on administrative boundaries created for a specific demographic coastal location and the issues being addressed (Anon 1995a, 1995b). Here, "coastal", depending on author, may be narrowly defined, or so broad as to encompass a wide variety of Holocene shoreline, Holocene near-shoreline, prograded Holocene shoreline complexes (such as beach-ridge plains, *cf.* Searle *et al.* 1988; or prograded tidal flats *cf.* Semeniuk 1981a, 1982), and former Quaternary shoreline landforms. In the Standing Committee on Environment, Recreation and the Arts, in a report titled *The Injured Coastline: Protection of the Coastal Environment* to the Australian House of Representatives, it was argued that there were three main approaches to defining a coastal zone (Anon 1991b), these being 1. administrative (based, for instance, on administrative boundaries or offshore legislative boundaries, and clearly not scientific), 2. linear (based on arbitrary boundaries such as a linear reference point, and therefore mostly cadastral), and 3. biophysical (based on physical features such as a mountain range, or a natural ecosystem, and not necessarily related to the coastal zone but to other conspicuous boundaries or features). These approaches are conceptually and scientifically flawed.

In this paper, the term *coast* will be used to denote the modern strip separating land and sea, and generally occurring between high and low tide, and the term *coastal* will be used to denote a variety of environments that relate to the interaction between oceanic and terrestrial processes. As such, these will contain both land and ocean components, and have boundaries to the land and ocean that are determined by the degree of influence of the land on the ocean and the ocean on the land; and may not be of uniform width, height, or depth (Kay & Alder 1999). These environments may include, for example, the seaward margin of prograded coastal plains, or coastal dune belts (where they have been formed by coastal processes), or areas influenced by marine processes such as salt spray. Stranded sea cliffs, of Pleistocene age or earlier, are not included in this definition of coast.

In this context, the term *coastal geoheritage* is used to denote geoheritage aspects of the coastal zone, where the coastal zone is the shore, and where terrestrial and oceanic areas are, or have been, influenced by coastal processes.

As noted above, sites of geoheritage significance can include features that range in size from crystals to geological features at the scale of mountains and landscapes (Figure 2 of Brocx & Semeniuk 2007). This size gradation and processes/products at various scales also occur in the coastal zone, with geomorphic features ranging from micro-pinnacles (also termed "lapiés" by some authors; *cf.* Guilcher 1953; Paskoff 2005) and tafoni, to specific types of cliffs, to large coastal (depositional) systems such as deltas. Scale is formally addressed in terms of frames of reference of fixed sizes (Table 1), using regional, large, medium, small, and fine scales (after Semeniuk 1986), or megascale, macroscale, mesoscale, microscale, and leptoscale (after C A Semeniuk 1987).

Table 1

Scales of reference for geomorphic and geoheritage features

Frame of reference	Descriptor
100 km x 100 km or larger	regional scale (or megascale)
10 km x 10 km	large scale (or macroscale)
1 km x 1 km	medium scale (or mesoscale)
10–100 m x 10–100 m	small scale (or microscale)
1 m x 1 m, or smaller	fine scale (or leptoscale)

That is, the frame of reference is used to denote those features evident at that particular scale. For instance, cross-lamination, sedimentary layering, lamination, bubble sand, shell layers, tafoni and micro-pinnacles ("lapiés") are evident within a 1 m x 1 m frame of reference, while larger cliff faces, shoreline benches and sandy spits are evident within a 10 m x 10 m or 100 m x 100 m frame of reference.

How is the coastal zone different from other environments?

The coastal zone is a special environment because it is a dynamic zone of intersection and interaction of land, sea, groundwater, and atmosphere. As a result, the coastal zone carries with it an abundance of processes and products that are not present in other environments or only weakly developed in those other environments. For instance, in contrast to the shore environment, nearby marine environments adjoining the coastal zone, though graded with respect to depth (with its attendant effects on wave energy intersecting the shelf floor, sediments, and biota), tend to be more homogeneous environmentally because the oceanic milieu itself tends to be relatively more uniform, and generally removed from processes such as wind, or fresh-water discharge (Kuenen 1950; Shepard 1973; Berger 1974; Ginsburg & James 1974; Swift 1974; Wilson & Jordan 1983; Swift *et al.* 1984; Collins 1988). As such, the complexities of shore processes and products generally are absent in the adjoining shelf environment The shelf may be underlain by a relatively uniform sheet of sediment (or rock), while the adjoining coast will comprise a range of sediments (or morphologic types cut into rock) that reflect the gradient of the effects of waves, tides, wind, and hydrochemistry that impinge on or interact with the shore.

This is not to imply that the terrestrial environment cannot also be complex, but in the terrestrial environment geological complexity generally is manifest in two ways: firstly, in the inherent structural, lithological and mineralogic variability in the underlying materials (though their expression as parent material is often diminished by weathering); and secondly, in weathering itself, which produces soils that reflect hydrochemical and geochemical processes acting on these materials. In fact, soils and palaeosols, resulting from hydrochemical interactions on various parent rocks, can present some of the most complex structural and geochemical products in the terrestrial environment (Hunt 1972; Buol *et al.* 1973; Arnold 1983; FitzPatrick 1983; Leeper & Uren 1993), particularly since the processes may have been operating over millennia, and this has already been recognised elsewhere (Gauld *et al.* 2003). While soils can express complexity in the terrestrial environment, the geodiversity (if developed) is usually at the geochemical level and in terms of pedogenic structures. However, soils generally do not exhibit the range and scale of features that can be developed at the coast.

Leaving aside soils, the degree of complexity in landform, geology, mineralogy, and groundwater, under conditions of a prevailing climate, developed on and in the materials in the terrestrial environment, at their most complex geological and lithological expression, will express this degree of geological complexity at the coast, with the added factor that coastal physical, chemical and biological processes superimpose other features on them. Thus the geological and geomorphological units of the terrestrial environment generally become more complex where they interface with, or are transformed at their interface with the sea.

In regards to soils, in coastal situations, soils mostly are stripped away from rocks at the shore, but if still present, they can become involved in complex hydrochemical interactions at the coast (driven, for instance, by sea spray, and groundwater seepage).

As the interface between land and sea, the coastal zone is subjected to a range of physical, chemical and biological processes, often graded in intensity normal to the shore gradient. These are listed in Table 2 (information drawn from Johnson 1919; King 1972; Schwartz 1972, 1973, 1982, 2005; Ginsburg 1975;

Table 2

The main physical, chemical, and biological processes operating in coastal zones

- wave action, comprising swell of various periods, wind waves, and standing waves, resulting in a plethora of wave patterns and wave lengths, variable temporally and spatially, and variable normal to the shore in terms of translational waves, shoaling waves, and breaking waves, with their attendant effects of erosion, sediment mobility, particle size sorting, sedimentary structure development; this is a prevailing phenomenon at the shore;
- storm action, and associated storm surges, with their attendant effects of erosion, sediment mobility, particle size sorting, sedimentary structure development, amongst other effects; this is an episodic phenomenon at the shore;
- cyclone activity and associated surges, with their attendant effects of erosion, sediment mobility, sedimentary structure development, amongst other effects; this is an episodic phenomenon at the shore;
- tsunamis and seismic-related surges, with their attendant effects of erosion, sediment mobility, sedimentary structure development, amongst other effects; these are episodic phenomena at the shore;
- longshore drift with its attendant effects of sediment mobility and particle size sorting;
- rip currents with their attendant effects of sediment mobility, particle size sorting, and development of bedforms and sedimentary structures;
- development of a splash zone; this is a prevailing phenomenon at the shore;
- onshore winds, acting on the near-shore marine water body, resulting in shore-directed wind waves, longshore drift, and other currents, and seiches; these are commonly linked to seabreezes/landbreezes systems
- onshore winds acting on the upper shore face of sandy coasts, with their attendant effects of erosion, sediment transport, particle size sorting, lag development, and dune building;
- shore sedimentation physically mediated by river influx, longshore and/or onshore wave transport, and tidal currents;
- shore sedimentation biologically mediated by *in situ* or proximal skeletal production (mainly carbonate, but also siliceous);
- pronounced bioerosion;
- chemical erosion of susceptible minerals and materials;
- wetting and drying in the splash zone and the high-tidal zone;
- salt weathering, particularly in high tide zones, and splash zones;
- diurnal to semi-diurnal tidal inundation, and attendant tidal-current processes that result in erosion, sediment mobility, particle size sorting;
- diurnal to semi-diurnal invasion of coastal sedimentary bodies by seawater during high tide;
- evaporation of pore water and shallow groundwater in high-tidal zones during low tide and neap tides, driven by solar radiation and/or wind, to develop moisture gradients and salinity gradients, and hence biological gradients and geochemical gradients;
- transpiration, resulting in depletion of pore water and shallow groundwater in high tidal zones during low tide and neap tides to develop moisture gradients and salinity gradients;
- hydrochemical effects such as precipitation of calcium carbonate (aragonite or calcite), gypsum, or halite, where evaporation has markedly concentrated coastal groundwater and pore water;
- hydrochemical and geochemical effects such as solution;
- fresh-water seepage in the subsurface through appropriate aquifers into sandy coastal zones with its attendant effects of coastal erosion
- fresh-water seepage in the subsurface through appropriate aquifers into the coastal zone with its attendant effects on coastal ecology;
- fresh-water surface discharge onto the coastal zone;
- sediment delivery to the tidal zone by fresh-water discharge onto the coastal zone;
- flora habitation, and its material contribution, encrustations, and bioturbation;
- fauna habitation, and its attendant material contribution, encrustations, biostrome and bioherm building, and bioturbation (for discussion of biostromes and bioherms see Cummings 1932, Nelson *et al.* 1962, and Kershaw 1994)

Davidson-Arnott & Greenwood 1976; Klein 1976; Davies 1980; Bird & Schwartz 1983; Inden & Moore 1983; Greenwood & Davis 1984; Kelletat 1995; Black et al. 1998; Komar 1998; Woodroffe 2002; Semeniuk 2005).

Many of the processes listed in Table 2 are absent in the terrestrial environment. Those that do occur (*e.g.*, chemical erosion of susceptible rocks/materials, hydrochemical and geochemical effects such as precipitation of calcium carbonate, and hydrochemical and geochemical effects such as solution of specific minerals), particularly along the shores of lakes and playas, are more amplified in the coastal zone, or because there is interaction with seawater, the effects of the processes are manifested differently.

The significant feature to note from Table 2 is the prevailing nature of many of the interacting processes in the coastal zone, the short-term temporal variability of some processes (*e.g.*, Allen 1984 discusses the temporal variability of processes along the coastal zone), and those processes that are not present in other Earth environments (*viz.*, oceanic wave action, or daily tides, and seabreezes/landbreezes). Many of the processes are acting concurrently. Aquatic or wetland terrestrial environments (such as salt lakes and rivers) exhibit some of these processes resulting in complexity along their shores (particularly salt lakes because of their hydrochemistry) but generally not to the same degree as marine coastal zones. Further, the periodicity of some of the processes in coastal environments is generally not equivalent to terrestrial environments. Where there *is* similarity of periodicity, the processes are of a different nature. For instance, the annual effect of storms on a sand-and-mud coastal zone, temporally may be viewed as equivalent to the annual flooding of a sand-and-mud river system, but the actual processes and lithologies generated are markedly different.

To illustrate the added complexity a coastal setting provides in contrast to a partly-equivalent terrestrial system, the processes operating, and the geodiversity developed, in an inland dune system in an arid region is compared to dunes in a beach-dune coastal system. An inland dune system can be variable and complex at the medium scale down to lamination scale and grain-packing scale, with landforms, sedimentary structures, and grain packing varying in response to temporal changes in wind direction and wind intensity (resulting in laminae formed by grain fall, slip-face avalanche, traction, saltation, particle sorting, winnowing, rippling, and ripple-migration; Bagnold 1941; McKee 1979; Brookfield & Ahlbrandt 1983; Allen 1984). These dunes may be flanked by a geomorphically and lithologically distinct inter-dunal systems (usually of inter-dune flats; Glennie 1970; Kocurek 1981; Lancaster 1988). For coastal dunes, notwithstanding that they are commonly bordered after progradation by stranded dunes (which may undergo increasing diagenesis towards inland), and to seaward by a beach, such dunes essentially carry the same set of processes and develop the same set of sedimentary structural and grain-packing features as arid-region dunes, but have added complications with grain behaviour and grain packing as a result of their content of equant to platey carbonate grains and porous carbonate grains. Further, coastal dunes are bordered by a complex stratigraphy to seawards, in the environments encompassed by the nearshore, swash zone, berm, and foredune. As such, while the dunes themselves may be more or less comparable, the package of a coastal beach-dune system will show more geodiversity than dunes and inter-dune flats located in an arid region.

Another feature which sets the coastal zone apart from terrestrial environments is the extent of biological activity, such as skeletal production, trapping and binding in a sedimentologically dynamic system, boring, bioturbation, and mediation of diagenetic effects. Skeletal grain production can have an effect on sedimentation patterns regionally: with increased skeletal grain production, and sediments can change from siliciclastic to a siliciclastic-carbonate mixture to wholly carbonate in composition. Biogenic particle content may dominate over siliciclastic particle content at the local scale, or may dominate sedimentary patterns regionally. This latter situation is exemplified, for instance, by the carbonate sediments and reefs of Shark Bay, the west coast of the Persian Gulf, the Bahama Banks, Florida Banks, and the Great Barrier Reef (Davies G R 1970; Logan & Cebulski 1970; Logan *et al.* 1970; Purser 1973; Logan 1974; Bathurst 1975; Scholle *et al.* 1983; Tucker & Wright 1990). So while siliciclastic sediments and carbonate sediments can share common physical processes in the shore zone (*viz.*, wave action, tidal-current effects, aeolian effects, amongst others), and thus can generate the same suite of physical sedimentary structures such as layering, cross bedding, and ripple drift lamination, if biogenic processes and products become dominant, they add a specific signature to products. And while siliciclastic sediments (accumulating either in the coastal or terrestrial environments) can form environment-specific fine-scale to large-scale complex sequences in their own right, if biological effects begin to exert an influence, biogenic structures such burrows and bioturbation may become dominant.

While all the interactive processes that can operate on accumulations of siliciclastic sediments in the coastal and terrestrial environment are present in the carbonate coastal suite, there is the added factor in the carbonate sediment suite that carbonate minerals such as aragonite, Mg-calcite and calcite (because of their relative and differential solubility) may hydrochemically and biologically interact with the environment to a greater extent than do siliciclastic sediment particles, *i.e.*, carbonate sediments are more susceptible to diagenesis than siliciclastic sediments. For example, carbonate grains are susceptible to algal micro-boring and marine weathering, and there is a large range of diagenetic products developed in the tidal zone (Logan 1974; Bathurst 1975; Tucker & Bathurst 1990; Tucker & Wright 1990).

Additionally, coasts commonly exhibit gradients normal to shore, *e.g.*, a gradient in inundation and evaporation, with attendant gradients in wave energy and tidal energy, and hence a graded expression of processes of sedimentation, erosion, and hydrochemical effects. This results in variable, complex and diverse physical, geochemical and biological products across the shore, and variation in fine- to small-scale stratigraphic sequences. As a consequence, many of the processes listed in Table 2, operating in the coastal zone, result in a gradational array of products across the coastal gradients. Responses to a concentration gradient in hydrochemistry is an example: there is precipitation of carbonate minerals and gypsum from high neap tide and high spring tide to highest tidal level. The discharge of fresh water into the coastal zone, where it mixes with seawater, or concentrated seawater, also can result in a range of chemical gradients and products, such as precipitates, or in biologically-mediated chemical changes. The discharge of fresh water in the coastal zone, with a rise and fall of the water table, particularly along steep, sandy beach shores (Clarke & Eliot 1987; Horn 2002), can also result in the erosion and accretion of the shores, and in the diurnal development of shoreline beach cusps (Kuenen 1948; Mu 1958; Guza & Inman 1975; Werner & Fink 1993; Komar 1998; Coco *et al.* 1999; Short 1999), with their resulting complex meso- and micro-stratigraphy and sedimentary structures (Mii 1958).

Both sandy beaches and tidal flats exhibit stratigraphic and sedimentological complexity, with the degree of complexity to some extent related to climate and oceanographic setting (for instance, beaches in tropical climates can develop beach rock, and signatures of cyclone activity through development of beach-rock boulder ribbons; *cf.* Semeniuk 2008).

Sandy beaches provide excellent examples of the products of wave and tidal energy intersecting a sloping shore, and illustrate the range of sedimentary products that are developed across the slope gradient from shallow subtidal to supratidal, in response to the graded effect of waves, tides, wind and fresh-water seepage (Beall 1968; Clifton 1969; Clifton *et al.* 1971; Reineck & Singh 1971; Davidson-Arnott & Greenwood 1976; Semeniuk & Johnson 1982; Inden & Moore 1983; Allen 1984; Semeniuk 1997; and see later). For instance, wave action intersecting a sloping shore is translated to a lower flow regime (varying progressively upslope) to upper flow regime, and the resultant development of rippled beds, megarippled bedforms, and plane beds, respectively. Hourly, daily, weekly and seasonal variation in wave patterns, coupled with storm effects, tide fluctuation, and onshore winds, generates lamination, shell layers, cut-and-fill structures, discontinuities (Mii 1958; Panin 1967; Boothroyd 1969), variation in grain size across laminations, and bubble sand. Biological activity results in shell layers, burrows, and bioturbation.

Tidal flats generally provide a greater degree of stratigraphic and sedimentological complexity than beaches because often they are sedimentary environments wherein there is accumulation and interaction of mud, sand, gravel, and biogenic material (Semeniuk 2005), and so are used here to illustrate the sedimentological and stratigraphic intricacies that can be developed along the shore zone. Tidal flats may be muddy, sandy, gravelly, or covered in shell pavements, and compositionally they may be underlain by siliciclastic or carbonate sediments or their mixtures. Depending on climate, tidal level, substrate and salinity, tidal flats may be covered by salt marsh, mangroves, sea grass, algal mats, microbial mats, biofilms, as well as mussel beds, oyster beds and reefs, and worm-tube beds and reefs, and inhabited by a burrowing benthos of molluscs, polychaetes, and crustacea (Semeniuk 2005). Tidal flats are rich in processes and products resulting from oceanographic, sedimentological, geohydrological, hydrochemical, and biotic interactions (Klein 1963, 1976; Ginsburg 1975; Alexander *et al.* 1998; Black *et al.* 1998). As lower-energy systems, with less scope for physical reworking, they develop a profusion of natural history coastal features reflecting the products of daily tidal inundation, prevailing translating/shoaling waves, wind, evaporation, and biogenic reworking. For instance, there are the sedimentologic products of interactions between waves and tides (*e.g.*, cross-laminated sand, ripple-laminated sand, lenticular bedding, flazer bedding, laminated mud, ripple-laminated silt in clay), the products of interactions between sediments and biota (*e.g.*, various burrow forms zoned tidally across the shore, various types of root-structuring, skeletal remains related to tidal levels), the geomorphic products of tides (*e.g.*, tidal run-off on low-gradient slopes to form meandering tidal creeks), and the products of hydrochemical interactions with sediments (*e.g.*, dissolution of carbonate by acidic pore water; cemented crusts and their intraclast breccia derivatives; carbonate nodules; gypsum precipitates; and products of redox reactions such as biologically-mediated precipitation of iron sulphide). The tidal zone is so diagnostic that for stratigraphers and students of sedimentary rocks, identifying this environment in the geologic record is often an important first step in the reconstruction of palaeo-environments, the location of facies associated with coastlines, and the recognition of such markers in stratigraphic sequences in basin analyses (Semeniuk 2005).

At the next scale, the scale of meso-stratigraphic and larger, the stratigraphic products and geomorphic products of coasts are unique from another perspective: coasts interface with oceans, and oceans, as the receiving basins of solar radiation, can propagate to the shore their history *via* sea temperatures, wave climate and storms. They also can imprint on the shore their record of sea-level changes. With progradation, the coastal zone thus has the potential to register and preserve a variable, complex and fluctuating oceanic and climate history from erosional products, sedimentation products, geomorphology (*e.g.*, beach-ridge patterns and cheniers, amongst others), and fossil biota. Through the recognition of appropriate sea-level indicators (or markers), coastal-zone stratigraphy, coastal-zone geomorphology, progradational shores, and rocky shores also have the potential to preserve records of sea-level changes (for Western Australia, see Semeniuk 1985; Semeniuk & Searle 1986; Playford 1988; Semeniuk 1997; and Semeniuk 2008).

A selection of products specific to the coastal zone that particularly well illustrate the special nature of the shore is listed below in Table 3 in terms of stratigraphy, sedimentary structures, lithologic products, biogenic structures, and diagenesis.

In the context of Table 3, in order to provide a perspective of the diversity and complexity of sedimentary structures and fine- to small-scale stratigraphic sequences in the coastal zone compared to terrestrial environments and deeper water marine environments, a review of variety of text books and sedimentological references, that illustrate sedimentary structures and fine- to small-scale stratigraphic sequences

Table 3

Some products specific to the coastal zone

Stratigraphic products
Example 1: upward-shoaling sequence developed by a prograding sandy beach where an inclined shore interfaces, intersects and interacts with waves, tides, onshore winds and storms; this is one of the best developed of coastal stratigraphic sequences, as it brings into focus the interplay of coastal processes, sediments, biota, and hydrochemistry (Beall 1968; Clifton 1969; Clifton *et al.* 1971; Semeniuk & Johnson 1982; Inden & Moore 1983; Allen 1984; Semeniuk 1997); depending on climate and tidal range, the stratigraphic products can change latitudinally, *e.g.*, occurrence of beach rock and cyclone-generated sediments (Semeniuk 1996, 2008)
Example 2: upward-shoaling sequence developed by a prograding siliciclastic tidal flat that granulometrically grades from low-tidal sand, to muddy sand to high-tidal mangrove-vegetated mud; this sequence also is one of the best developed of coastal stratigraphic sequences, because it provides a plethora of sedimentary and stratigraphic products that are the result of a wide range of grain sizes, a stronger effect of the tides across tidal gradients, a stronger effect of biota because of the relatively lower energy setting, and the effects of hydrochemistry graded across the tidal flats; again (Thompson 1968; Ginsburg 1975; Semeniuk 1981a; Semeniuk 2005); depending on climate and tidal range, the stratigraphic products can change latitudinally, *e.g.*, occurrence of displacive gypsum and development of mangrove facies (Logan 1974; Brown & Woods 1974; Semeniuk 2005)
Example 3: upward-shoaling sequence developed by a prograding algal mat and stromatolites on a carbonate and evaporate tidal flat (Kendall & Skipwith 1969; Shinn *et al.* 1969; Logan *et al.* 1974)
Lithologic products
Example 1: beach rock conglomerate and breccia (Semeniuk 1996, 2008)
Example 2: shoreline coquina (Logan *et al.* 1970)
Example 3: intraclast breccia sheet (Hagan & Logan 1974; Logan 1974)
Sedimentary structures
Example 1: tidal flat sedimentary structures and layering such as bidirectional ripple cross-lamination, flazer bedding (Reineck & Singh 1980; Shinn 1983)
Example 2: flazer bedding (Reineck & Singh 1980)
Example 3: bubble sand within an upward-shoaling beach sand sequence (Emery 1945; Semeniuk & Johnson 1982; Inden & Moore 1983; Semeniuk 1997)
Biogenic structures
Example 1: U-shaped faunal burrows (Reineck & Singh 1980)
Example 2: stromatolitic layering and emergent structures showing smooth, tufted and pustular fabrics (Logan *et al.* 1974)
Example 3: lithophagic borings (Semeniuk & Johnson 1985)
Diagenetic products
Example 1: beach rock, cemented bands or layers (Ginsburg 1953; Semeniuk 1996, 2008)
Example 2: nodular gypsum replacing carbonate tidal flat sediments (Kendall & Skipwith 1969; Shinn 1983)
Example 3: precipitate aggregates forming nodules on shells or crustacean skeletons (Semeniuk 1981b)

from a diverse range of depositional systems was undertaken (Allen 1984; Bathurst 1975; Berger 1974; Bird & Schwartz 1985; Cas & Wright 1988; Collins 1988; Collinson & Thompson 1982; Cooke & Warren 1973; Conybeare & Crook 1968; Davies 1970; Davies 1980; Davis 1978, 1994; Davis & Ethington 1976; Duncan *et al.* 1992; Fisher & Smith 1991; Ginsburg 1975; Ginsburg & James 1974; Greenwood & Davis 1984; Hopley 1982; Inden & Moore 1983; Kelletat 1995; Kendall & Skipwith 1969; Klein 1976; Le Blanc 1976; Logan 1970, 1974; Matthews 1984; Middleton 1965; Morgan 1970; Pettijohn & Potter 1964; Potter *et al.* 1980; Purser 1973; Reading 1978; Reineck & Singh 1980; Rigby & Hamblin 1972; Scholle & Spearing 1982; Scholle *et al.* 1983; Semeniuk 1981a, 1996, 1997, 2008; Semeniuk & Johnson 1982, 1985; Shinn 1983; Shinn *et al.* 1969; Snead 1982; Swift 1974; Tillman & Siemers 1984; Tucker & Wright 1990; Walker 1979; Warme *et al.* 1981; Wilson & Jordan 1983). While there is a degree of overlap, and some of the sedimentological and stratigraphic features dominant in coastal settings *can* occur in terrestrial sedimentary settings, though they are uncommon (*e.g.*, water escape structures, bubble sand, U-shaped burrows), the coastal environments provide the greatest diversity and complexity of physical, chemical and biological structures and products and environment-specific features. Bubble sand provides an illustration of this: bubble sand (as small trapped air pockets in sand) can occur in shoreline deposits adjoining lakes, and locally on sandy levees, but it is very uncommon. However, it is prevalent on coasts where there is wave action and a rising tide on a sandy beach – here it is a diagnostic feature of the upper-tidal zone of the beach (Semeniuk & Johnson 1982; Inden & Moore 1983; Semeniuk 1995).

The review showed that complexity, and development of environment-specific sedimentary structures and fine- to small-scale stratigraphic sequences are particularly evident biologically. This is because different areas of the Earth's coastal environments, depending on biodiversity (related to biogeography), climate, and type of coastal system, have varying coastal biota, and biota often form particular assemblages across the shore in response to gradients in wave energy, tidal level, salinity, substrate type, and grain size, amongst others (*e.g.*, mangroves in tropical muddy environments, saltmarsh in temperate muddy environments, mussel beds in low-tidal muddy environments). Some biota in specific settings develop coastal (tidal) biostromal or biohermal accumulations, for example, biostromal mussel beds (in The Wash and along the coast of North Wales, and the Wadden Sea; Yonge 1949; Evans 1965; Wolff 1983), or serpulid worm (biohermal) reefs (along the coasts in Eire, Scotland, and the Gulf of Mexico; Andrews 1964; Bosence 1973, 1979; Ten Hove & van den Hurk 1993).

To further illustrate the complexity of interacting processes and diversity of products that develop across a shore environment in contrast to terrestrial environments, several examples of sedimentary coastal systems and rocky-shore systems are described and compared below to (approximately) equivalent materials and sequences in terrestrial environments to contrast their geodiversity. For instance, upward-fining sequences involving sand and mud from a point bar is compared to an upward-fining sequence involving sand and mud from a tidal flat. In the range of comparisons provided, we have endeavoured to remain within the same climate setting as there has to be some measure of internal consistency in the environmental setting for comparisons to be meaningful.

It is this range of sedimentological, erosional, and diagenetic features, described above, and their strength of development that sets coastal geoheritage apart from continental (or inland) geoheritage.

Comparisons of the coastal zone with inland systems – a contrast of geodiversity

A range of rocks, sediment sequences, and lithologies occurring in the coastal zone are compared to terrestrial environments. Some of the comparisons are of directly equivalent rocks exposed in coastal and terrestrial environments. For sedimentary sequences, the comparisons are between coastal sediments and their stratigraphic sequences and sediments and stratigraphic sequences occurring in broadly lithologically similar materials in terrestrial environments. Comparison is also made with two other relatively complex environments, *viz.*, karst, and (active) volcanic terrains. The comparisons are intended to highlight the complexity and geodiversity of one environment in relation to the other. The examples are as follows (Figure 1):

1 a comparison between a fluvial ravine and a rocky shore, using the Tumblagooda Sandstone as the parent material;

2 a comparison between a natural inland cliff/ravine and a rocky shore, using a Pleistocene calcarenite as the parent material;

3 a comparison between an upward-shoaling stratigraphy of a point bar and an upward-shoaling tidal flat stratigraphy;

4 a comparison between the micro-stratigraphy of a mud-dominated floodplain and mud-and-sand floodplain and that of a mud-dominated tidal flat.

The multiplicity of interacting processes operating on a sandy beach and on a calcarenitic rocky shore is illustrated in Figures 2 and 3.

The Tumblagooda Sandstone exposed along the coastal rocky shores shows a wide variety of small-scale and fine-scale features not evident in the same Formation in fluvial ravine settings. Of particular importance is the effect of salt weathering in the coastal zone resulting in better exposure of lithology and sedimentary structures (Figures 1A–1D), the development of tafoni, structural benches (where bedding-plane features are well exposed), the wave-cut benches, pavements and slopes planed by marine processes, and the intertidal cementation. Structural benches exposing bedding-plane features on soft lithology such as shales, are recessively weathering in the fluvial ravines.

The contrast in geodiversity for Pleistocene calcarenites between natural inland cliff/ravines and the coastal zone is similar (Figures 1E–1H): the coastal exposures show more geodiversity than calcarenites occurring in inland exposures in terms of small-scale and fine-scale geomorphology, and in effects of coastal diagenesis. The coastal outcrops are also better exposed as a result of wave-washing, wind erosion, and salt weathering. The difference in geodiversity between a sedimentary sequence developed in an upward-shoaling tidal flat and that of an upward-shoaling stratigraphy of a point bar also is marked, with the former illustrating the products of intricate interaction between waves, tide, wind, and biota, and the latter showing a less developed assemblage of sedimentary structures and lithology (Figures 1E to 1H). The intricacies of physical, chemical and biological processes acting on tidal flats result in suites of lithologies, sedimentary structures and sedimentary products not developed in the point bar (Figures 1I–1J). In fact, the point bar, without a fluctuating floodwater level is a relatively simple stratigraphy and sequence of sedimentary structures. The final example, contrasting the micro-stratigraphy of a mud-dominated tidal flat with the micro-stratigraphy of a mud-dominated floodplain and a mud-and-sand floodplain shows, again, that the tidal-flat sequence in terms of sedimentary structures, lithology and biological effects is more complex and diverse, reflecting the interaction of particle sizes, tides, waves, inundation frequency, hydrochemical gradients, and biota (Figures 1K & 1L). Even though the scale of stratigraphy is somewhat different, the floodplain sequences show relative monotony of lithology, while the tidal flat mud sheet shows relative richness of features at the fine scale evident as lamination, burrows, burrow-mottling, flazer bedding, mud cracks and mud flakes.

Differences between coastal and terrestrial environments is well highlighted by contrasting a sandy beach system with fluvial sands. There is a marked difference in geodiversity between a sedimentary sequence developed under a beach in a microtidal setting, in terms of lithology, structures, and small-scale stratigraphy, in comparison to sand shoals in a sand-dominated river systems. As mentioned earlier, the beach sequences show the graded effect of waves, tide, wind, and biota on a sandy slope. There can be hourly, daily, weekly to seasonal adjustment of the beach profile in response to waves, the formation of beach cusps, and the cutting of cliffs in sand, as well as seasonal accumulation of storm deposits, amongst other effects, with the result there is a complicated layered and cross-layered stratigraphy, and scour-and-fill structures, bounded by discontinuities (Mii 1958; Panin 1967; Boothroyd 1969). Beach processes, sedimentology, and stratigraphy are summarised in Figure 2. In contrast, sand shoals in sand-dominated river systems exhibit a much less complicated sequence of laminated and cross-laminated sands. More complex stratigraphy in such systems occurs where there are lag concentrates of coarse sand and gravel, and where mud accumulates (and then dries and desiccates) in the troughs between megaripples and shoals.

In the examples presented above, the coastal zone manifests lithologically better exposed rocks and stratigraphic sequences, and sedimentologically more complex products and stratigraphy than the terrestrial environments.

This emphasis on the coastal zone is not intended to diminish geological complexity elsewhere. Other environments do have geodiversity, and it may be expressed in a variety of ways as will be illustrated by a brief synopsis of karst environments, volcanic settings, and landscapes developed by arid zone erosion.

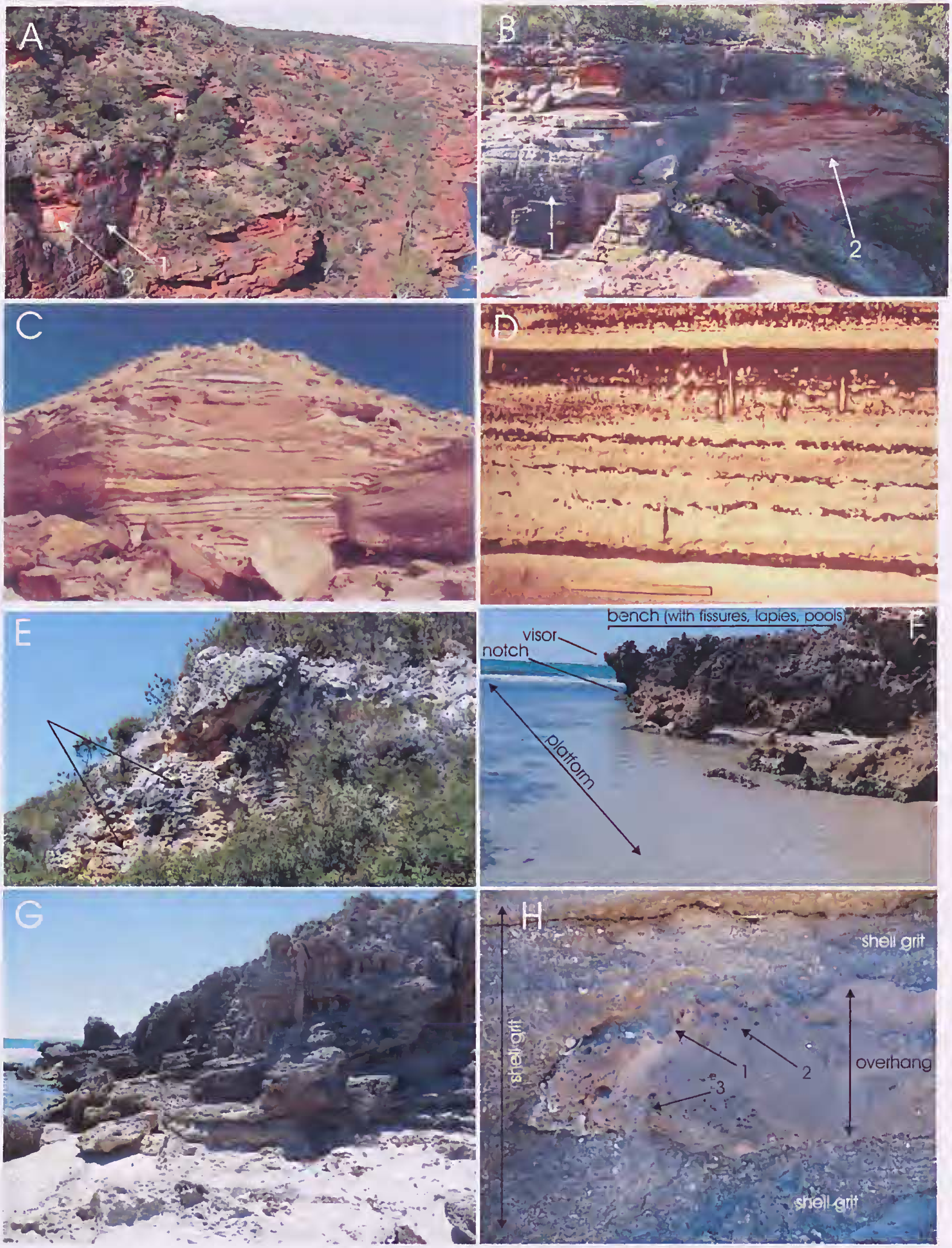
The karst environment, for instance, with its array of cave forms, sedimentology, and crystal development in drapes, sheets, curtains, stalactites and stalagmites, straws and helical structures, and the interlayering of crystal deposits and sediments is a complex and diverse environment, with diversity particularly expressed in the arrangement of crystal aggregates and their interaction with sedimentary fill (Cullingford 1953; Jennings 1971; Waltham 1974; Jakucs 1977; Gillieson 1996). Similarly, volcanic settings can be complex and (geo)diverse (Cas & Wright 1988; Fisher & Smith 1991). They may comprise variable magmas, lava-flow sheet and ribbon bodies and accompanying structures (*e.g.*, breccia, vesicules), the interactions between lava, water and atmosphere, the generation of ash, the interaction of volcanic products (such as ash) with rain, hot springs, magmatic waters and their mineralogic products, gas exhalations and their mineralogic products, and volcanogenic sedimentation, all of which result in a wealth of diverse geological features, from large scale to fine scale to mineral/crystal scale. Extinct volcanic terrains, with erosion, also generate a range of interesting and variable landscapes that are founded on the diversity of geological structures such as plugs, dykes, ash layering, and lava rivers, amongst others.

From the information above, it would seem that active volcanic settings could rival coastal settings for complexity and geodiversity, but while volcanic settings manifest a variety of products, coastal environments carry with them factors that add complexity beyond that developed in volcanic terrains. Coasts, as described above, generally manifest a greater geodiversity than some of other more complex terrestrial environments, including karst and volcanic environments, not only because the coastal zone is the "interaction zone" of a large number of processes, but also because, unlike other terrestrial systems, there is variation in processes temporally (at the scale of minutes, hours, days, weeks, months, and years), at the fine to small scale spatially, and latitudinally (regional scale spatially) which result in various expressions of coastal sedimentary deposits depending on terrigenous influx, climate, biodiversity, shelter, wave climate, tidal range, and coastal wind. For sedimentary bodies, for instance, in the shorter time frames, this can result in various expressions lithologically and at the scale of sedimentary structures: lamination and scour-and-fill in beach stratigraphy, responding to wave effects, and responding to the development and destruction of beach cusps, respectively, are the result of short-term temporal variation affecting sedimentary sequences on sandy coasts; flazer bedding in tidal flat stratigraphy responding to semi-diurnal tide and wave effects, is the result of temporal short-term variation affecting sedimentary sequences on tide-dominated, sand-and-mud coasts. For sedimentary bodies in the longer-term time frames, temporal changes in the coastal processes can result in changes in sedimentary style, stratigraphy, and sediment geometry.

Erosion of massifs in arid regions by wind, water, and salt-weathering also can result in locally well-exposed cliff faces to the same level of detail as in coastal cliff sections, particularly where wind erosion is involved. The stratigraphic sequences in Monument Valley, Arizona (USA), the Navajo Twins in Bluff Sandstone and other sandstone cliffs in south-east Utah (USA), the Ennedi Massif in the Sahara Desert (Chad, Africa), the Jebel Acacus in Libya (Africa), and ironstones exposed in the gorges of the Hamersley Ranges (Western Australia) exemplify this (Holmes 1966; MacLeod 1966; Cooke & Warren 1973; Oberlander 1977; Schlüter 2005).

Discussion

Geoconservation is concerned with the protection and management of geological sites for the preservation of special outcrops, palaeontological, mineral, and pedological localities, geoarchives that represent a page from the Earth's history, locations where Earth processes are active, locations that are representative of the Earth's


A
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bench (with fissures, lapies, pools)
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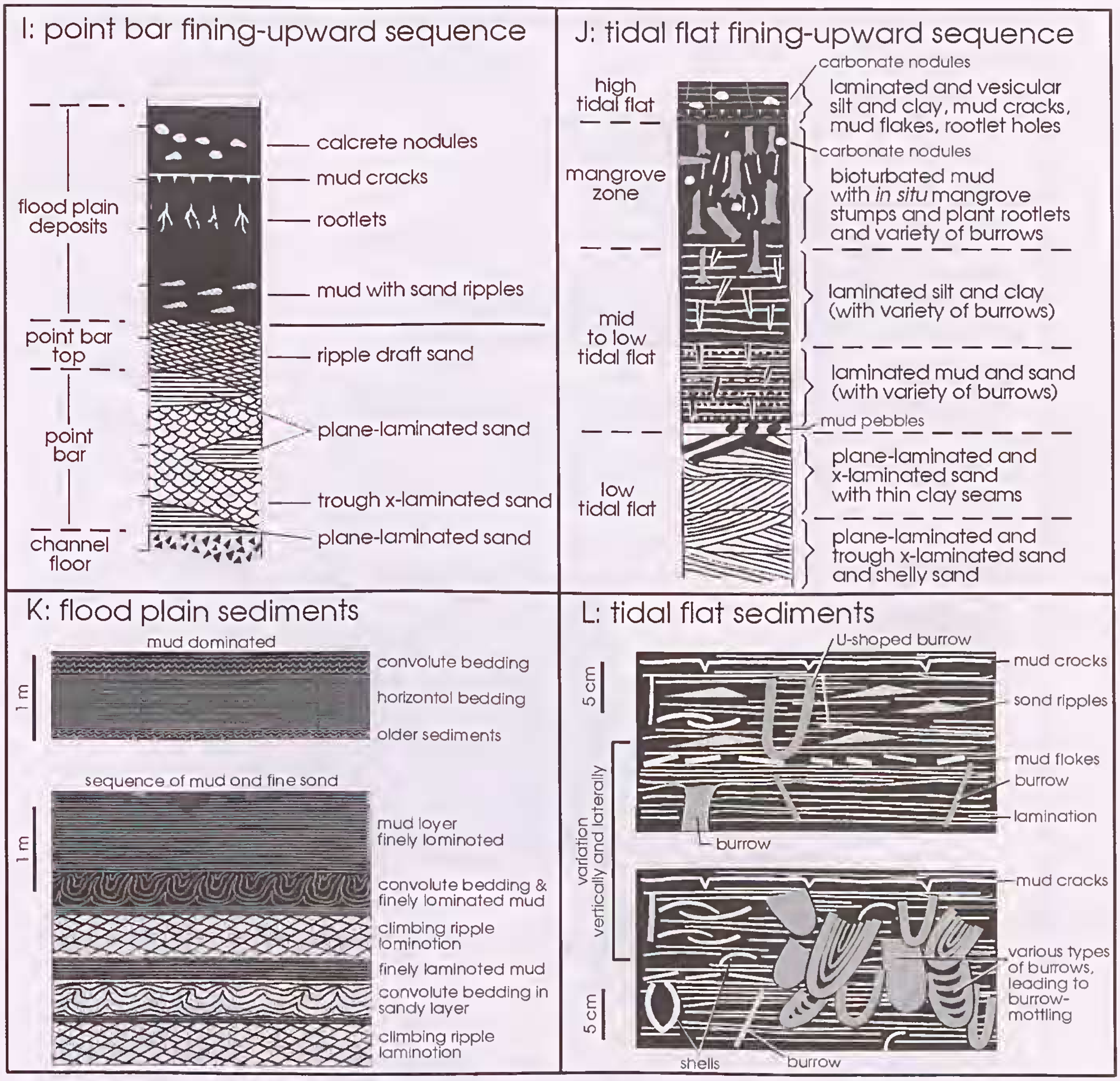

Figure 1. Contrast between terrestrial and coastal geodiversity. A–D. Outcrops of the Tumblagooda Sandstone. A & B. Outcrop of the Tumblagooda Sandstone in Murchison River gorge near Kalbarri. The walls of the gorge do not expose well the lithological and structural details of the Formation, in that joint-controlled vertical cliffs usually are iron oxide coated (1), and the general outcrop is weathered. Recent rock falls exposed weathered rock (2). C. Wave-washed, wind-eroded, and salt-weathered cliff face of the Tumblagooda Sandstone at Red Bluff, Kalbarri showing well exposed lithological and structural features. A large channel-form is clearly evident in the cliff, and layering is prominent and traceable. D. Close-up of (C) showing lithological and structural details of trace fossils and layering (scale is 30 cm). E–H. Outcrops of Pleistocene calcarenites. E. Outcrop of calcarenite along a natural cliff several kilometres from the coast, showing crusted surface, and poor exposure of lithological and structural features. Some lamination is arrowed. The base of the cliff is covered in sand (as fans) and breccia. F. Coastal exposure of calcarenite in the Perth area, showing range of geomorphic features (platform, notch, visor, bench with micro-pinnacles or lapiés) developed as a result of shore erosion and solution of Pleistocene calcarenite at North Beach, Western Australia. G. Rocky shore exposure of calcarenite at Muderup Rocks (Cottesloe, Western Australia) showing well exposed stratigraphic, structural and lithological features brought out by wave erosion, salt weathering and wind erosion, *viz*., prominent lamination and cross-lamination. H. Rocky shore exposure of calcarenite at Muderup Rocks showing well exposed laminated shell grit (arrowed interval), unconformably overlying (and underlying) a rocky shore overhang in older calcarenite; the overhang is hard band, bored by echinoids (1), pholadids (2), and other lithophagic organisms (3); see Semeniuk & Johnson (1985). I & J. Contrasting upward-fining sedimentary sequences of a terrestrial system (a point bar) and a coastal system (a tidal flat). I. Point bar stratigraphy showing structures in sand, fining up to a mud sequence (modified after Walker 1979). J. Tidal flat stratigraphy showing structures in sand, in the interlayered mud and sand, and in mud (modified after Semeniuk 1981a). K & L. Contrasting the details of a mud sheet and a mud-and-sand sheet formed in a terrestrial system (a floodplain) with that of a mud sheet formed on a tidal flat. Note that the structures and lithology of the floodplain sediments are expressed over an interval of a metre or more, while the intricate details of structures in the mud of a tidal flat occur within an interval ~ 20 cm. The comparison is intended to contrast the relative monotony of a floodplain sequence with the relative richness of features evident in tidal flat mud deposits. K. Details of structures of the mud sheet and a mud-and-sand sheet formed on a floodplain (information adapted from McKee 1966; McKee *et al.* 1967; Walker 1979 and Potter *et al.* 1980). L. Details of structures of a mud sheet formed on a tidal flat (information adapted from Reineck & Singh 1980 and Semeniuk 1981a, 2005).

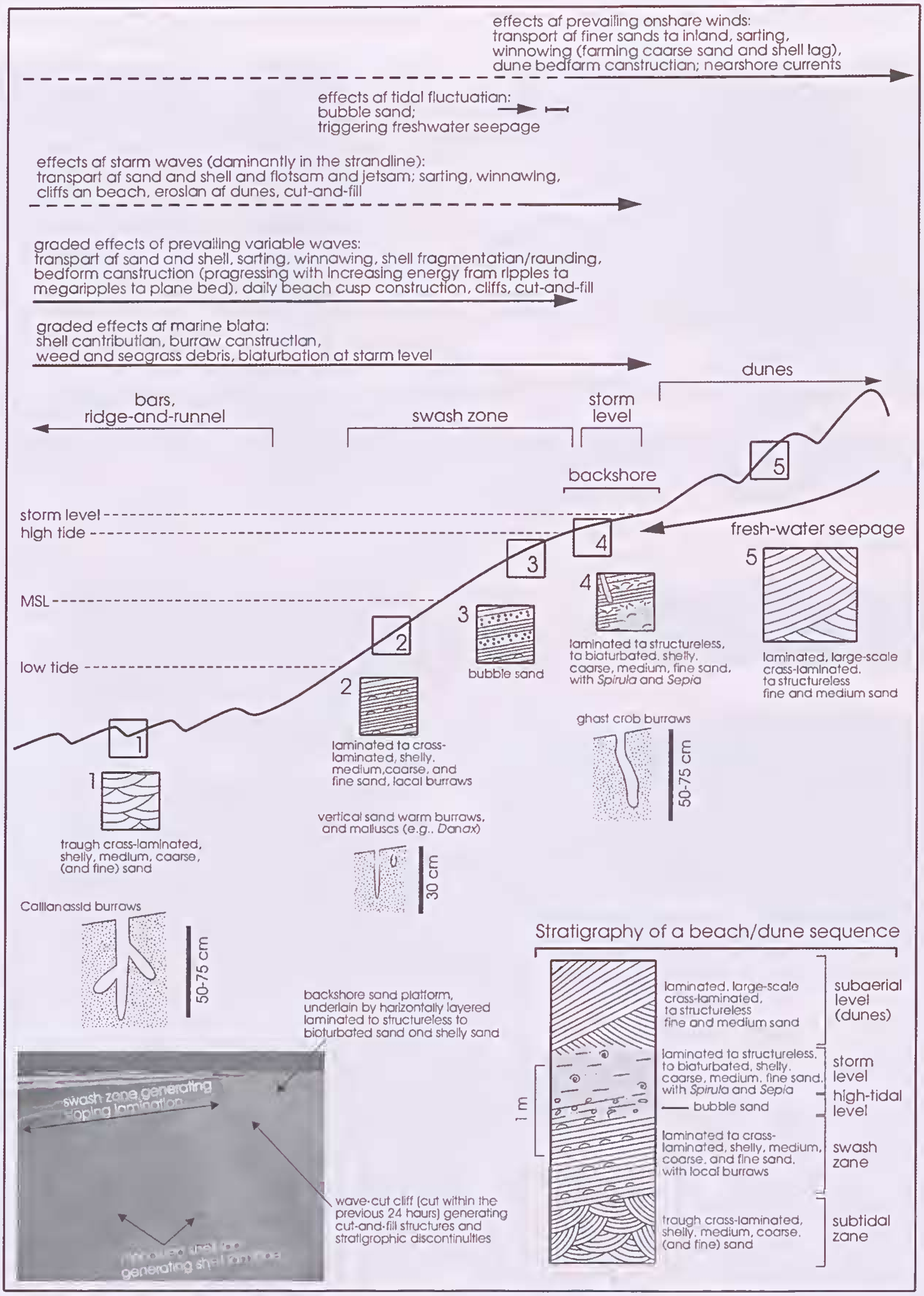

Figure 2. Processes and products on a sandy beach (graded across the beach). Waves, tides, wind, fresh-water seepage, and biota interact with a sloping sandy shore producing a range of sedimentary products related to the slope gradient (information from Mii 1958; Panin 1967; Beall 1968; Boothroyd 1969; Clifton 1969; Clifton *et al.* 1971; Reineck & Singh 1971; Davidson-Arnott & Greenwood 1976; Semeniuk & Johnson 1982; Inden & Moore 1983; Allen 1984; Semeniuk 1997). The stratigraphy generated by lateral progradation and shoaling of the beach is also shown. The photographic inset shows the surface of a beach: selected geomorphic and sediment units of the beach are noted, with description of the types of sediments and structures that underlie them. The sand cliff marking the edge of the berm was cut within the previous 24 hours of the photography.

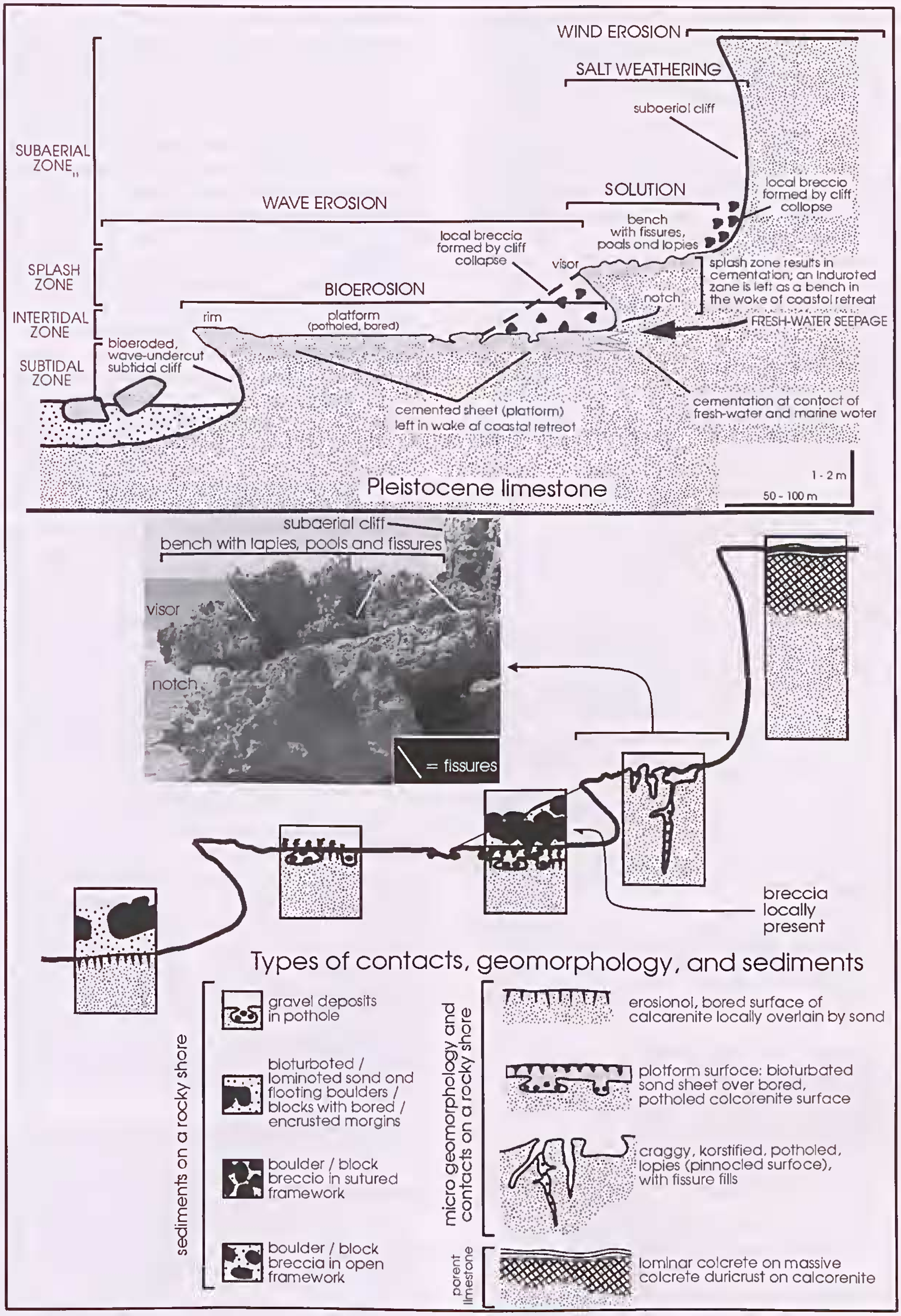

Figure 3. Processes and products on a rocky shore cut into Pleistocene calcarenite. Waves, tides, wind, fresh-water seepage, and biota interact with and have modified the calcarenite geomorphically, chemically, mineralogically and biologically (information from Wentworth 1938; Edwards 1941; Emery 1945; Hills 1949; Fairbridge 1950; Guilcher 1953; Emery & Foster 1956; Emery & Kuhn 1956; Bird & Dent 1966; Semeniuk & Johnson 1985; Stephenson 2000). The small-scale stratigraphy and geomorphic features at various levels along the rocky shore, generated by erosion, sedimentation, and biota, are also shown: The photographic inset shows details of the notch, visor, and the craggy nature of the bench (with lapiés, pools, and fissures).

geodiversity, and sites that are of cultural significance (Sharples 1995; Barettino *et al.* 1999; Brocx & Semeniuk 2007; Brocx 2008; Erikstad 2008). The coastal zone is especially significant in a context of geoconservation because, as emphasised in this paper, of all the environments on the Earth's surface, it is one of the most complex in terms of landforms developed, sedimentological processes and products, and diagenetic processes and products, manifesting high geodiversity of Holocene landforms, stratigraphy, sedimentology, and diagenesis. It also exposes some of the best and most detailed outcrops (globally, including Western Australia) where geological history can be readily investigated. Such exposures have the potential for high geoheritage significance, and indeed some cliff exposures already have been afforded global and national geoheritage significance either because of their geological importance (the cliffs in Dorset and East Devon, and along the Sussex coast in the United Kingdom), or because of their cultural importance (the unconformity at Siccar Point, Scotland).

As a result of the interactions between the various processes, and between processes and products along the shore compared to terrestrial environments and submarine environments, a large range of physical, chemical, structural, and biological features and environment-specific features occur in the coastal zone. In addition to the complexity of forms, the interactions of land, sea, groundwater and atmosphere along the coastal zone, occurring at all scales, result in a grade in sizes of many of the coastal products. For sedimentary bodies, this ranges from the (larger-scale) geometric forms of sedimentary deposits down to the scale of laminae and grains. For eroding rock sequences, this ranges from cliffs to benches to tafoni and micro-pinnacles ("lapiés") to structures and grains etched out in relief.

As such, the coastal zone is an environment where there should be a focus on geoconservation.

As noted earlier, the emphasis on the geodiversity of the coastal zone in this paper is not intended to diminish the importance of geological complexity elsewhere, but rather to point out the geological richness of natural features developed along the coastal zone, the nature of coastal outcrops compared to inland sites, and to provide some explanation of why the coastal zone displays geodiversity to the extent that it does.

In this paper we have highlighted the reasons that the coastal zone generally has greater geodiversity in terms of geomorphology, sedimentology, and diagenesis than some of the other complex environments: because it is the "interaction zone" of a large number of marine, terrestrial, groundwater and atmospheric processes, and because, in contrast to terrestrial, marine and volcanic systems, there is variation of geological processes and products temporally and spatially, with the variation depending on the coastal setting, the extent of terrigenous influx, climate, biodiversity, shelter, wave climate, tidal range, and coastal wind.

Temporal variation occurs in the time-frames of minutes, hours, days, weeks, months, and years for the processes involving waves, tides, winds, storms, cyclones, and fresh-water discharge. For sedimentary bodies, in short-term time frames, this can result in various expressions lithologically, and at the finer scales, in diverse sedimentary structures. In long-term time frames, this can result in changes in sedimentary style, stratigraphy, and sediment body geometry. Laminae in sand in the swash zone of beaches, varying in grain sizes or grain packing, can be reflecting variation in transport, winnowing, or grain-size sorting under the effect of waves and currents fluctuating in intensity in time frames of minutes or less. Annual storms, or cyclones returning perhaps on a decadal basis, can result in larger-scale sedimentological and stratigraphic responses such as the development of major scours and cliffs, development of shoreline spits, emplacement of gravel sheets and bars, or development of shell pavements by winnowing processes.

Spatial variation is from fine to small scales to regional scale (latitudinally). At fine to small scales, this may be expressed in shore-normal gradients in wave energy, tides, and hydrochemistry, that result in variation in geodiversity across the shore. Variation upslope in lithology, bedforms, and sedimentary structures reflect gradients in wave and tidal energy. Variation upslope in types of precipitates reflect gradients in hydrochemistry. At regional scales, spatial variability can be expressed in latitudinal (climatic) and environmental gradients, with other factors such as riverine influx and hinterland geology being equal. For instance, in Western Australia, latitudinal (climatic) gradients are expressed in the variation in landforms, coastal erosion, and diagenesis of Pleistocene calcarenites from their most southern occurrence along the Leeuwin-Naturaliste Ridge to their outcrop along the Zuytdorp Cliffs, a distance of over 1000 km. The variation within the Quindalup Dunes of Holocene coastal dune forms, landform assemblages, sediment types and their diagenesis, from their most southern occurrence in Geographe Bay to their most northern occurrence at Dongara (Semeniuk *et al.* 1989), is another example of differences expressed along a latitudinal (climatic) gradient. Changes in style of development of parabolic dunes serve as an example. Within this belt of Quindalup Dunes, Semeniuk *et al.* (1989) show that along the climate gradient, with change in wind direction and wind intensity, the coastal parabolic dunes change from short-axis easterly-ingressing generally simple and relatively small parabolic dunes in southern areas of the Swan Coastal Plain, to short-axis northeasterly-ingressing fretted larger parabolic dunes in central areas of the Swan Coastal Plain, to long-axis northerly-ingressing markedly attenuated (hairpin) and linearly extensive parabolic dunes in northern areas.

At the most fundamental level, leaving aside biogenic input, the coast modifies the hinterland by interacting with it. Being a "ribbon" environment, or viewed globally, a relatively thin "linear" environment, the coast traverses topography, variable geology and structures, oceanographic settings, climate of the coast and climate of the hinterland, tidal ranges, biogeography, and sedimentary style (*e.g.*, delta-dominated, or barrier-dominated, or carbonate sediment dominated, amongst others). The coast is the most widespread linear environment on Earth. By definition it is circumferential to all landmasses facing the marine environment and thus inherently holds the largest potential to be the most variable environmental interface on Earth. And therein lies the reason for its geodiversity, and why coastal geoheritage within the umbrella of geoheritage has been emphasised in this paper. By way of contrast, volcanic systems, which earlier in this paper are recognised as having characteristics of high geodiversity, are not so consistently interconnected, even if portrayed as being in a "ring of fire" (*e.g.*, the "Pacific ring of fire"; Sutherland 1995; Murphy & Nance 1998). They tend to create their own volcanic environment and its environmental subsets, and create their own range of products from magma interacting with bedrock geology, water and atmosphere. While exhibiting high geodiversity at the local scale, at the global scale volcanic systems tend to be "nodal".

An outcome of the effect of erosion in the coastal environment is that coasts generally provide excellent locations for studying rock sequences (sedimentary, igneous, or metamorphic). Fine- to small-scale rock structural features, intra-lithologic features, and various lithologic types are brought out best by coastal erosion effected by wave washing, (sand-charged) wave erosion, wind erosion, and salt weathering. A corollary is that the exposures along the coast are often also the best outcrops for type sections and reference locations. The chalk cliffs of the southern coast of the United Kingdom, the stratigraphy exposed along the coast of Devonshire in the United Kingdom, the unconformity at Siccar Point in Scotland, and in Western Australia, the Tumblagooda Sandstone at Kalbarri, the Broome Sandstone at Gantheaume Point, and the Toolinna Limestone along the edge of the Nullarbor Plains, exemplify this.

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